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ORIGINAL ARTICLE

A study on carbon dioxide emissions from bituminous coal in Korea

Jeongwoo Lee · Chang-Sang Cho · Ki-hyup Hong · Jae-Hak Jeong · Seungjin Kim · Eui-Chan Jeon

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Abstract Consumption of primary energy in Korea increased 5.25 % per year over a 10 years span starting in 1990. Korea ranked 8th in primary energy consumption in 2011; coal consumption increased 35 % from 87,827 million tons in 2006–119,321 tons in 2010. Heavy energy-consuming countries consistently conduct research to develop an emission factor of Tier 2 level, reflecting the characteristics of the fuel that they use. To calculate the emission factor of bituminous coal for fuel, this study developed emission factor and calculated emission amount by implementing fuel analysis on bituminous coal consumed in Korea between 2007 and 2009. CO_2 emission factor calculated by fuel analysis method is 95,315 kg/TJ, which is 0.75 % higher than the default value suggested by IPCC. The emission amount calculated by using the CO_2 emission factor in this study is 231.881 million tons, which has a difference of 1.739 million tons compared to the IPCC default value.

J. Lee
Department of Earth and Environmental Sciences, Sejong University, 98 Gunja-dong Gwangjin-gu, Seoul 143-747, Korea

C.-S. Cho · J.-H. Jeong · S. Kim
Cooperate Course for Climate Change, Sejong University, 98 Gunja-dong Gwangjin-gu, Seoul 143-747, Korea

K. Hong
Department of Climate Change Action, Korea Environment Corporation Environment Research Complex, Kyungseo-dong, Seo-gu, Incheon 404-708, Korea

E.-C. Jeon (✉)
Department of Environment and Energy, Sejong University, 98 Gunja-dong Gwangjin-gu, Seoul 143-747, Korea
e-mail: ecjeon@sejong.ac.kr

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Introduction

The consumption of primary energy in Korea increased 5.25 % per year from 1990 to 2000. The amount was recorded at 243.3 million TOE (tons of oil equivalent) in 2009 (The Republic of Korea 2011). While Korea imported 87.9 % of the energy it consumed in 1990, the amount rose to 96.4 % in 2009, which is equal to USD $91.16 billion (KEEI 2011).

Korea ranked 8th in primary energy consumption in 2011 (BP 2011). Coal consumption increased 35 %, from 87.827 million tons in 2006 to 119.321 million tons in 2010. Under the circumstances, Korea, a heavy energy-consuming country, implemented the Law on Low Carbon and Green Growth and established greenhouse gas reduction policies based on the national framework of Low Carbon Green Growth. In addition, the government set a goal for greenhouse gas reduction, energy saving, and efficient energy use, and is implementing Greenhouse Gas Target Management.

According to the Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4), global warming and climate change is an unavoidable fact, and each country is developing its GHG inventory to reduce GHG emission (Specter 2009; Department of Climate Change and Energy Efficiency 2012; Federal Environment Agency 2012; Huo and Li 2012; Mallia and Lewis 2012). The 2006 IPCC Guidelines propose IPCC default factors; however, when calculating national GHG emission, it recommends applying country-specific emission factor reflecting characteristics of GHG emission (IPCC 1996, 2006).

Heavy energy-consuming countries consistently conduct research to develop an emission factor of Tier 2 (country-specific value) level, reflecting the characteristics of the fuel that they use (Quick and Glick 2000; Sheng and Li 2008). GIR (Greenhouse Gas Inventory and Research Center of Korea) has performed research estimating greenhouse gas emission in Korea. In addition, greenhouse inventory and developing emission factor from coal fired power plants and cement plants using bituminous coal have been studied by researchers (Song et al. 2007; Yoon et al. 2008; Jeon and Sa 2010; Lee et al. 2011).

However, the 3rd country report submitted by Korea in 2011 calculated emission amount using emission factor of Tier 1 (IPCC default factors) level. In order for Korea to calculate an accurate amount of greenhouse gas emission, the development of Tier 2 emission factor is recommended. Coal is the second most consumed energy in Korea, as of 2010. Bituminous coal accounts for about 20 % of total energy consumption, being consumed in various ways, mainly in power generation and as industry fuel. However, there has been not much research on a country specific emission factor of bituminous coal for fuel in Korea.

Fuel analysis method for energy sources and concentration analysis method for emission gas are the primary methods used for calculating the amount of greenhouse gas emission (IPCC 2006). To calculate the emission factor of bituminous coal for fuel (Tier 2 level), this study developed an emission factor and calculated emission amount by implementing fuel analysis on bituminous coal consumed in Korea between 2007 and 2009. In addition, this study analyzed the exhaust gas released from power plants that use bituminous coal in real time, to measure the concentration of CO_2 and calculate its emission factor. Then, the emission factor of CO_2 was compared with the emission factor that was calculated in this study.

Methods

Coal sampling methods

Approximately 810 bituminous coal samples were used in this study, which originated from Australia (330), Indonesia (170), China (160), Russia (93), and others (US, Canada, Republic of South Africa: 57) from 2007 to 2009.

Sampling of coal is a process of preparation where the coal is cut, reduced, and ground. The sampling of bituminous coal in this study was implemented based on the ASTM D 2013 (2011), which is shown in Fig. 1. According to ASTM D 2013 (2011), it is permissible to air dry the sample before crushing. Samples may require air drying to feed properly through the reduction and dividing equipment. Sometimes there is an interest in determining the air dry loss value before crushing. Reduce the gross or divided sample to a top size of 4.75 mm (No. 4) or 2.36 mm (No. 8) sieve taking precautions. If the initial crushing was only to 4.75-mm sieve size, reduce to 2.36-mm sieve size after dividing to no less than the quantity specified for a 4.75-mm sieve size. With suitable pulverizing equipment, reduce the 2.36-mm sieve size subsample to a 250-μm (No. 60) sieve size. Divide the ground subsample by riffling, using the small riffle until a minimum of 50 g is obtained.

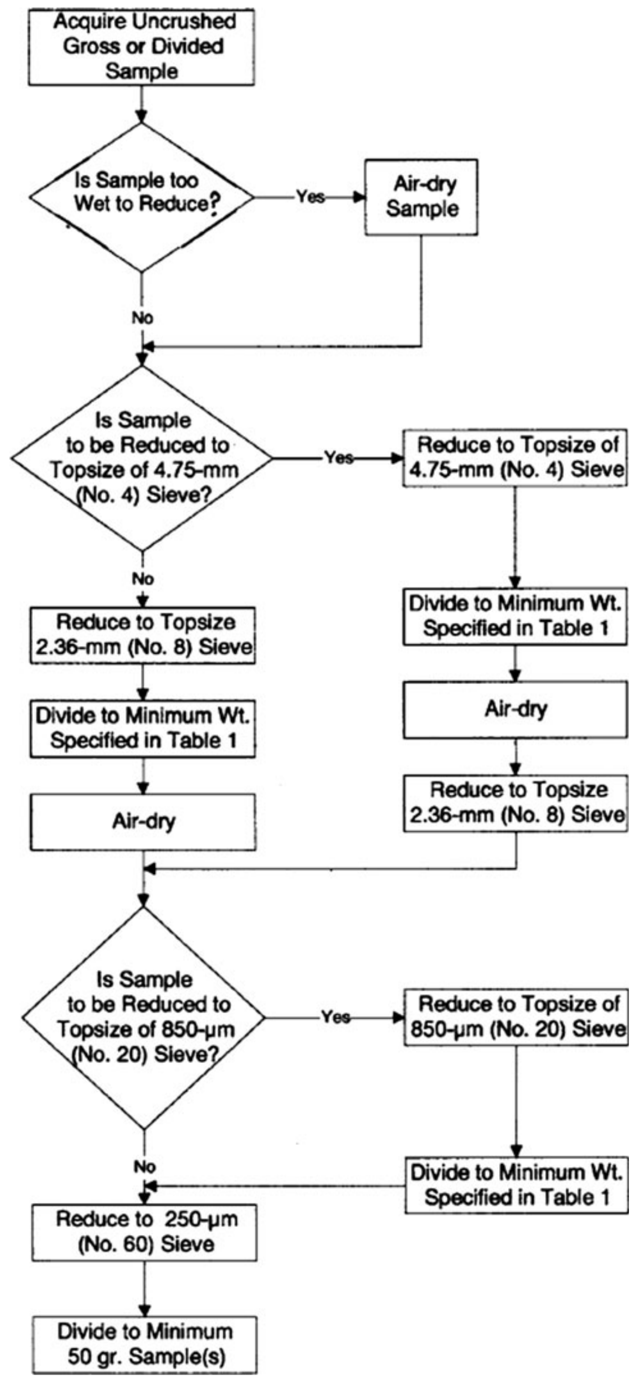

Fig. 1 Sampling Preparation Flowchart (ASTM D 2013 2011)

There are two kinds of coal sampling, manual sampling and sampling by machine. Samples are collected, ground, and mixed through these methods. The mixed samples go through reduction and grinding, and finally are shaped into 250 μm of particles. Next, they are stored airproof (ISO 1988 1975; ASTM D 2013 2011-10 2010). Bituminous coal for fuel was collected and analyzed through this process.

Analysis method

Coal analysis method

Calorific values are needed to convert the units into energy units, such as Joule. In addition, Carbon, Hydrogen, Nitrogen, and Sulfur, which are the main components of fuel, as well as moisture (adherent moisture, inherent moisture), ash, volatile components, and fixed carbon, all have great influence on combustion characteristics. Carbon, in particular, concerns the production of CO_2 in the process of combustion (Jeon et al. 2006). Thus, calculating the emission amount of greenhouse gases and emission factor is very important (IPCC 1996; Roy et al. 2009). This study mostly used ISO (International Organization for Standardization) and ASTM (American Society for Testing Materials) in fuel analysis. Air-dry analysis and dry analysis were used in analyzing the calorific value and elements, respectively. This paper converted calorific values based on 'As Received Basis' to compare CO_2 emission factors, because IPCC suggests calorific value based on the 'As Received Basis'.

A Type-B calorimeter was used to analyze the calorific value of 1 g of sample. This study used a calorimeter (IKA-C2000, Germany) to analyze the calorific value of coal. This machine is used to calculate the total calorific value of liquids and solids, consisting of a "bomb" that heats by burning samples, and a water temperature controller (IKA-KV600, Germany) that maintains the temperature difference. The calorific value was analyzed at 25 °C with an isoperibolic calorimeter, and the water temperature controller was set at 20 °C (ISO 1928 1995; ASTM D 5865-10 2010).

As for element analysis, CO_2 and vapor are absorbed into the absorbent after the sample is heated and burned, and then the percentage of carbon and hydrogen is calculated based on the total amount of the anhydrous sample. This study used an automatic element analyzer (Thermo Finnigan-Flash EA 1112, USA). Dynamic Flash Combustion method was used to oxidize compounds, separated with column, and then analyzed with TCD (ASTM D 5373-08 2008; ASTM D 3176-09 2009).

Gas analysis method

In order to calculate CO_2 emission factor, this study measured the concentration of CO_2 using NDIR (Non-dispersive infrared absorption), which is equipped in CEM (continuous emissions monitoring). NDIR method was used to measure CO_2 in the paper written by Pandey et al. (2007), Stephens et al. (2011).

In the NDIR method, IR radiation is launched from an infrared source and passes through a gas filter wheel and a bandpass filter. A certain IR wavelength goes through a reference cell that is charged with inert gas (Nitrogen, Argon), and a sample cell in which the sample flows in turn. IR wavelength passes through a reference cell and is absorbed by CO_2 in a sample cell. Absorbency is indicated on the IR Detector, and then converted and amplified to calculate concentration (Wang et al. 2005; Frodl and Tille 2006).

Estimation of emission factor

Estimation of emission factor

The emission amount of greenhouse gases generated by adherent combustion is calculated by multiplying the amount of fuel consumption by emission factor. This study used fuel analysis method (IPCC 1996; Quick and Brill 2002) suggested by IPCC that consists of a five-step worksheet to calculate CO_2 emission factor of bituminous coal. The first step is examining the amount of carbon and water, which have the biggest influence on the emission amount of CO_2. The amount of carbon is changed into the 'As Received Basis' amount at this stage. The second step is examining the production amount depending on the fuel consumption and standardizing the energy unit. A unit of calorific value TJ is standardized into net caloric value. The third step is calculating the actual amount of carbon emission by applying the values produced in steps 1 and 2, as well as the oxidation quotient. The fourth step is calculating CO_2 emission factor depending on activity (amount of energy and fuel use) by multiplying carbon emission amount by 44/12. The fifth step is calculating carbon emission by analyzing CO_2 emission factor depending on the activity produced in step 4 (Jeon et al. 2006).

Gas analysis type

A calculation method based on the actual measurement suggested by IPCC was used to calculate an emission factor, which is produced by analyzing CO_2 concentration. The first step is applying an average concentration of CO_2 and the flow, which are measured for 30 min. The second step is calculating low caloric power, by analyzing the fuel used in the facility as well as its amount. The third step is calculating the emission amount of CO_2 by multiplying the average concentration of CO_2 and the integrating flow of exhaust gas. The amount of CO_2 was measured every 30 min in a unit of tons. Then, the measurements were

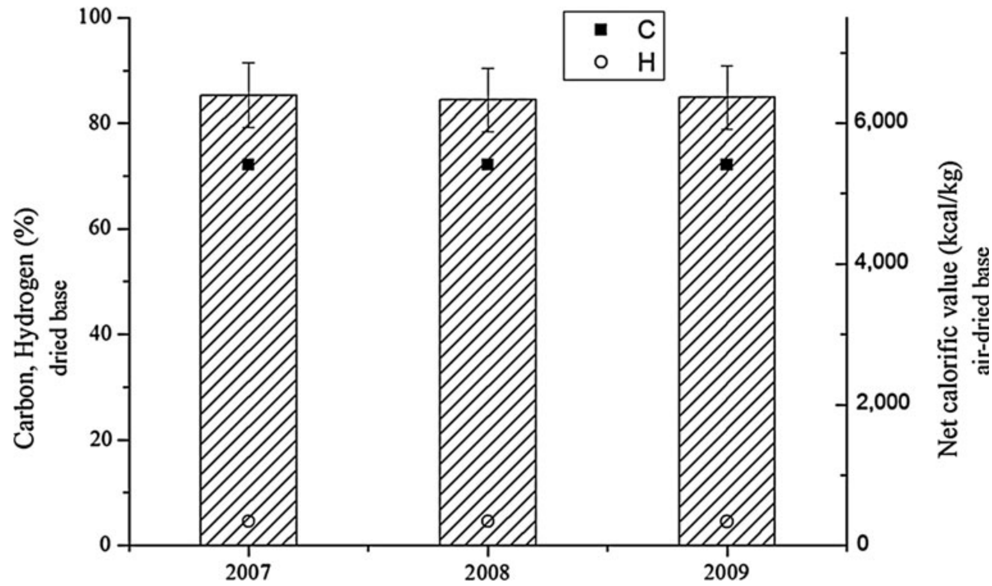

Fig. 2 Comparing with net calorific value, C and H of bituminous coals in Korea

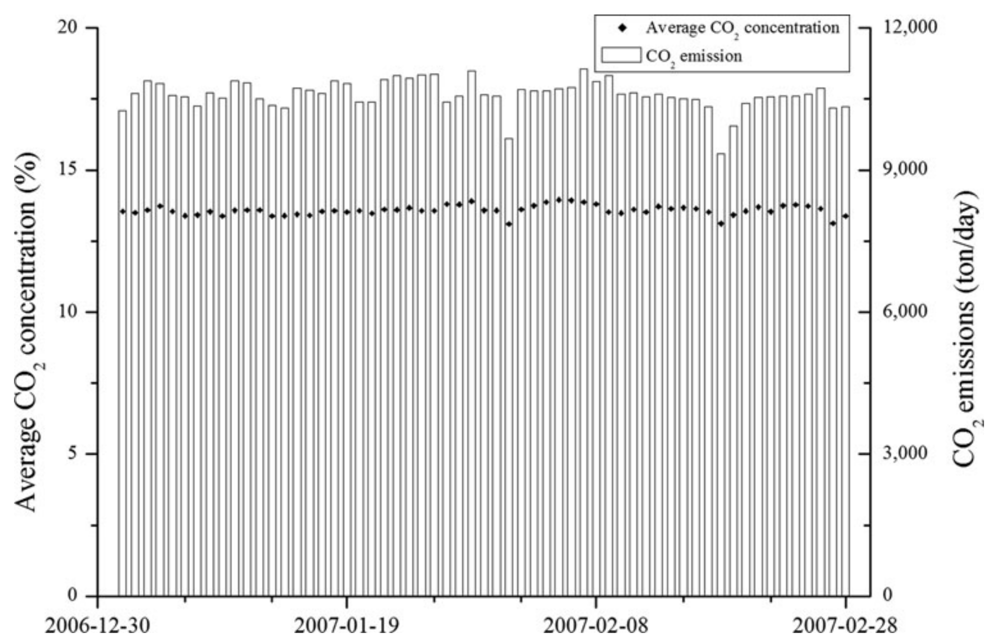

Fig. 3 Average of CO_2 concentration and emissions in bituminous coal fired power plant

added up to calculate the emission amount. The fourth step is applying the total emission amount of CO_2. The fifth step is calculating the emission factor of CO_2 by multiplying the emission amount of Carbon and 44/12, then dividing it by activity.

Results and discussion

QA/QC

In order to identify the credibility of the laboratory data, this study compared the calorific value analysis, element analysis, and technical analysis with other laboratories' analyses. Standard samples were used to assess the reproducibility of the calorific value analyzer. An electronic scale with 0.1 mg accuracy was used to weigh the samples. The average calorific value of the standard sample was $6{,}323 \pm 4.27$ kcal/kg, which is the result of five occurrences of repetitive analyses. The margin of error with a calorific value of standard sample was about 9 kcal/kg. Relative standard deviation among samples was 0.07 %, which is excellent reproducibility.

BBOT (2,5-bis (5-tert-butyl-benzoxazolyl)thiophene) standard sample was used to assess reproducibility of the element analyzer. About 1.6 mg of sample was injected

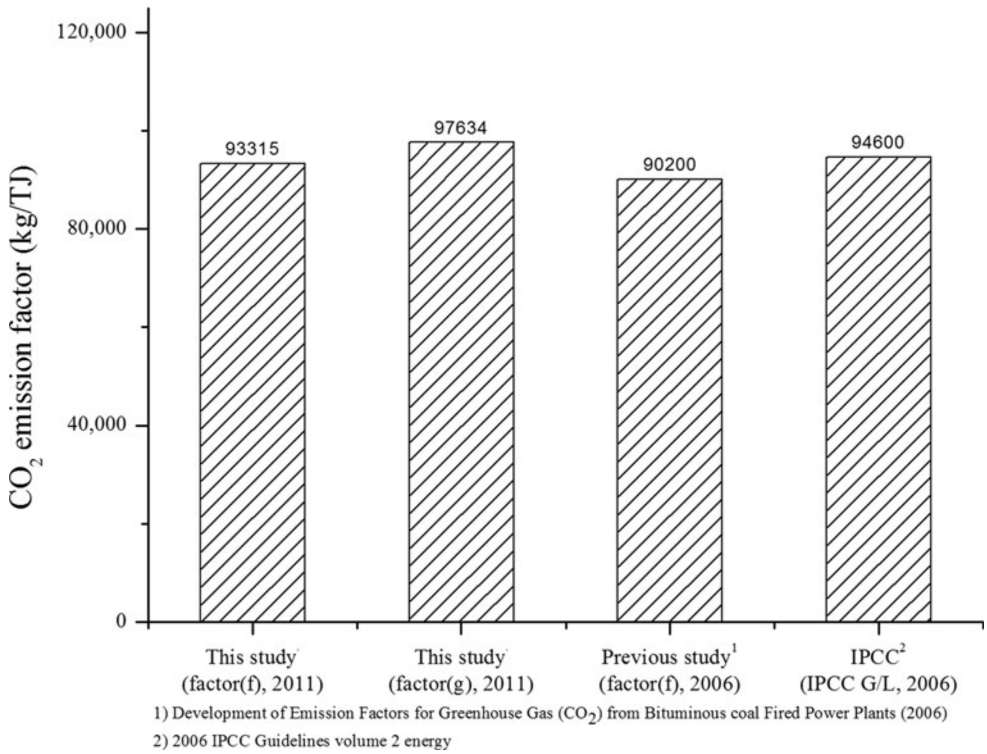

Fig. 4 Compare CO_2 emission factors in this study

into a precision balance, which can weigh up to 0.001 mg. A 2-m long column (ParaQX) used to analyze elements and flow was set at 140 mL/min of carrier gas, 240 mL/min of oxygen, and 100 mL/min of reference gas. The furnace and oven were set at 900 and 70 °C, respectively. The standard sample was analyzed three times in the same manner. As a result, the absolute difference was 0.01–0.12 % for carbon and 0.01–0.07 % for hydrogen.

The CEM measuring equipment was given approval after passing the regulation on formality and accuracy, according to the 'Law of Management System in Environment'. In order to maintain the function of CEM measuring equipment and secure the credibility of measuring data, the equipment is examined for accuracy a minimum of yearly after it is installed. In the examination for accuracy, the Zero and Span[1]concentration of the sample gas are injected into the measuring equipment to maintain the credibility of the measuring value.

Fuel analysis results of bituminous

Figure 2 shows the result of analyzing the calorific value and element for bituminous coal that was used in Korea from 2007 to 2009. Carbon amount in bituminous coal was 72.16 % in 2007, 72.10 % in 2008, 72.13 % in 2009, and 72.13 % on an average. Hydrogen amount in bituminous coal was 4.56 % in 2007, 4.57 % in 2008, 4.50 % in 2009, and 4.54 % on an average. The calorific value of bituminous coal is 6,399 ± 455 kcal/kg in 2007, 6,330 ± 448 kcal/kg in 2008, 6,367 ± 451 kcal/kg in 2009, and 6,363 ± 428 kcal/kg on average.

Gas analysis results of bituminous

Figure 3 shows the CO_2 concentration, which is measured at a power plant using bituminous coal. The average CO_2 concentration was 13.58 ppm. The low caloric value based on 'As Received Basis' (ARB) was 6,019 kcal/kg, and the emission amount of CO_2 released during the research period was approximately 10,596 tons.

CO_2 emission factor of bituminous coal

Figure 4 shows the emission factors calculated in this study, the emission factors calculated by other institutions, and the emission factor suggested by IPCC. While the bituminous coal's CO_2 emission factor [factor (f)] calculated in this study is 95,315 kg/TJ, the CO_2 emission [factor (g)] of gases released from a power plant that uses bituminous coal is 97,634 kg/TJ. The CO_2 emission factor suggested by IPCC is 94,600 kg/TJ, which is 0.75 and 4.09 % higher than factor (f) and factor (g), respectively. Factor (f) is 5.37 % higher than 90,200 kg/TJ, which was calculated in previous research conducted by Jeon et al. (2006).

[1] A concentration of standard gas between 95 and 105% of "the maximum value of the measuring range" is designated as a span concentration.

The amount of bituminous coal in 2009 was 98.602 million tons and the average caloric value based on the air-dried basis (ADB) was 6,363 kcal/kg, which were calculated using the emission factor and the CO_2 emission amount produced in this study. The CO_2 emission amount calculated by factor (f) and factor (g) were 231.881 million tons and 239.956 million tons, respectively. The CO_2 emission amount calculated using IPCC default value is 230.142 million tons, which is 1.739 million tons higher than the amount calculated using factor (f).

Conclusions

This study calculated the emission amount of greenhouse gases produced in the consumption of bituminous coal for fuel in Korea, as well as the emission factor. The fuel analyzing method suggested by IPCC G/L was used in calculating CO_2 emission factor, which was compared with the CO_2 emission factor of gases released from a power plant that uses bituminous coal as fuel. Korea imports all of the bituminous coal it consumes from Australia, China, and other countries. The average calorific value of the bituminous coal consumed as fuel in Korea over the past 3 years is 6,363 kcal/kg, which is 142 kg/kcal lower than the amount of 6,505 kg/kcal calculated in previous research. CO_2 emission factor (f) and factor (g) were 95,315 kg/TJ and 97,634 kg/TJ, respectively. Factor (f) was closer to the default value suggested by IPCC, compared with factor (g). CO_2 emission amount calculated by using factor (f) was 231.881 million tons.

This gap was generated because emission factor and emission amount changed due to an annually changing calorific value. Korea implements a notification amendment of energy calorific value every 5 years according to Enforcement Regulation of Energy Law. The Notification Amendment is used as a database when calculating emission factor and emission amount of greenhouse gases in the country. Korea imports all of the bituminous coal it consumes from several countries, from several mines in each country.

Therefore, the government should continue to carry out this type of research in order to calculate a credible emission factor, because the calorific value and the amounts of Carbon, Hydrogen, and inherent moisture of bituminous coals are changeable.

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